Chapter 19
Characterization of a Visco-Hyperelastic Synthetic Gel for Ballistic Impacts Assessment

A. Bracq, G. Haugou, B. Bourel, R. Delille, C. Maréchal, F. Lauro, S. Roth, and O. Mauzac

Abstract Understanding the human body response during impact has become a primary concern, especially in the field of ballistic impacts. Among various materials employed as human body substitutes, synthetic gel named SEBS is used in the present study. Mechanical characterization from quasi-static to very high strain rates are performed allowing the constitutive modeling of the gel material and its implementation in an explicit finite element code. Tensile testing are completed using appropriate tensile fixtures and specific strain measurement and point out a hyperelastic behavior (strain over 300%) with strain rate sensitivity. Compression tests are performed from static strain rates to dynamic strain rates using for very high strain rates polymeric split Hopkinson bars and high-speed imaging. Mooney-Rivlin hyperelastic material model with specific strain rate dependence is implemented using optimization process by inverse method of dynamic compression testing results for material parameters identification. The material law is employed during modeling of direct impact of less lethal kinetic energy projectiles over various velocities and gives satisfactory results compared to the experimental impact analysis.

Keywords Soft tissue simulant • Mechanical characterization • High strain rate • Constitutive modeling • Impact modeling

19.1 Introduction

The past decade had seen the rapid increase in ballistic impact studies, especially to understand the human body response, as well as to improve protective equipment. Among various materials employed as human body substitutes such as ballistic gelatin, clay and rubbers, a synthetic gel named SEBS (styrene-ethylene-butylene-styrene) has shown many benefits such as its transparency, mechanical consistency and environmental stability [1, 2]. Then it leads the French Ministry of the Interior to adopt this soft material as tissue simulant for blunt ballistic impact analysis. Although gel transparency allows direct impact analysis using high-speed camera and provides information on the back face deformation as wall displacement, volume of deformation, these macroscopic information do not allow a direct evaluation of a blunt ballistic trauma. Thence the authors focus their research on the use of numerical tools as finite element method for impact modeling to obtain more accurate data and extend information as strain, strain rate, pressure. Indeed, recent studies have studied ballistic blunt trauma and more precisely behind armor blunt trauma (BABT) through finite element modeling [3, 4]. However to obtain proper data, a material model must be determined to correctly describe its mechanical behavior over a large range of strain rates with experimental tensile and compressive testing.

The compliant nature of the gel and its low mechanical impedance require the use of adequate device. A previous research on SEBS gel depicts an interesting fixture design as well as strain measuring method to obtain valid and expendable tensile testing. Moreover, authors have dedicated their study on the mechanical characterization of the SEBS gel in compression at

---

A. Bracq (✉) • G. Haugou • B. Bourel • R. Delille • C. Maréchal • F. Lauro
Laboratory LAMIH UMR 8201 CNRS, University of Valenciennes and Hainaut Cambrésis, 59313, Valenciennes, France
e-mail: anthony.bracq@univ-valenciennes.fr

S. Roth
University of Bourgogne Franche-Comté, University of Technology of Belfort Montbéliard, 90010, Belfort, France

O. Mauzac
French Ministry of the Interior, CREL/SAELSI, Place Beauveau, 75800, Paris Cedex 08, France

J. Kimberley et al. (eds.), *Dynamic Behavior of Materials, Volume 1*, Conference Proceedings
of the Society for Experimental Mechanics Series, DOI 10.1007/978-3-319-62956-8_19

high strain rates [5]. They use the well-known Hopkinson bars or Kolsky bars to obtain the material response [6]. As several authors, polymeric split Hopkinson bars are adopted to correctly characterize the compressive behavior of such soft materials at very high strain rates [7, 8]. However, literature review is not sufficient to obtain usable true stress-strain curves over a wide range of strain rate for the studied material. Actually, SEBS gel is obtained by mixing SEBS powder and mineral oil producing 30 wt% SEBS with a styrene/elastomer ratio of about 30/70. Consequently tensile and compressive testing are performed at very high strain and strain rates using dedicated machine and measuring system.

19.2 Experimental Study

Based on literature, tensile testing are conducted using aluminum fixture with a specific design including the tensile sample [2]. Indeed, fixture shape allows to the sample to be only maintained by its shoulders. Black spots are drawn on the specimen, their local deformation leads to calculate the true stress-strain response. Actually, through the use of high-speed camera, measuring the black spot deformation, it results in the longitudinal and transverse strain measurements. It conducts to the validation of incompressible material assumption, quasi-constant engineering strain rate as well as homogeneity of deformation. Several tests are performed from 0.07 to 59.5 s^{-1} and true stress-strain curves at different strain rates are presented in Fig. 19.1 (left). It can be highlighted that the material has a hyperelastic behavior (strain over 300%) with a strong strain rate dependence. Conventional compressive tests are also completed over a range of strain rate. It is important to note that, despite the use of lubricant, only engineering stress-strain curves can be presented until 40% strain in Fig. 19.1 (right). Likewise, a strain rate sensitivity is pointed out, where the stress increases with the strain rate.

During ballistic impacts, the gel block used as soft tissue simulant is subjected to very large compressive at dynamic strain rates. Therefore, extensive effort is made to characterize the material at very high strain rates. Polymeric split Hopkinson pressure bars (SHPB) of 20 mm in diameter are employed along with high-speed camera to observe the specimen deformation during loading. Dedicated data processing software is adopted to determine the material response through the analysis of strain gauges recording data placed on the input and output bars.

Experimental apparatus and material low impedance result in the gel mechanical response from 440 to 1520 s^{-1}. Figure 19.2 presents typical strain gauges raw signals allowing the material characterization. However, even though multitude of precautions are undertaken, high-speed imaging reveals non-homogeneous deformation during loading which prevents the use of stress-strain curves determined at high strain rates for direct material constitutive modeling. Nevertheless, modeling compressive testing, especially the Hopkinson bars can be employed to identify material model parameters and will be depicted afterwards.

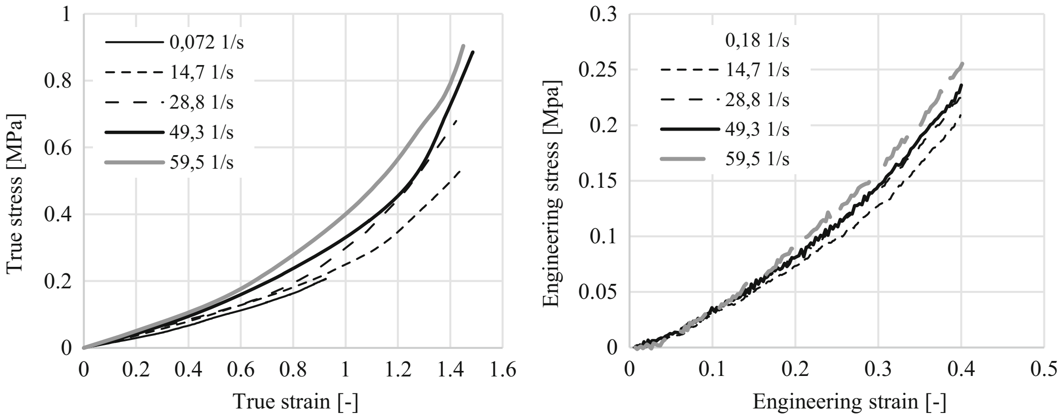

Fig. 19.1 True stress-strain curves from tensile testing (*left*) and engineering stress-strain curves from compression testing (*right*) at various strain rates

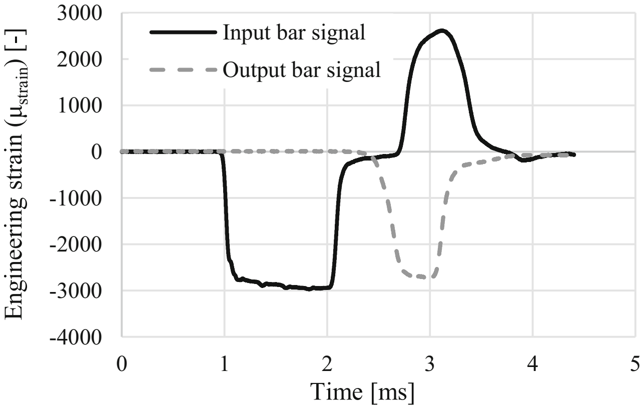

Fig. 19.2 Recording from strain gauges for dynamic compression testing at 1520 s^{-1}

19.3 Numerical Study

As experimental testing highlights a hyperelastic behavior, the authors take an active interest in hyperelastic material models. Ogden material model is one of the most use to describe non-linear material response until 600–700% strain [9]. This model can be described with a strain energy density function Eq. (19.1) based on principal stretch.

$$W(\lambda_1, \lambda_2, \lambda_3) = \sum_{k=1}^{N} \frac{\mu_k}{\alpha_k} \left(\lambda_1^{a_k} + \lambda_2^{a_k} + \lambda_3^{a_k} - 3 \right) \tag{19.1}$$

For particular values of material constants ($N = 2, \alpha_1 = 2, \alpha_2 = -2$), Ogden model can be reduced to the Mooney-Rivlin material model [10]. This latter model is chosen for the few parameters to identify. Each mechanical testing is assumed to be at constant strain rate. In such case, model parameters can be identified for each strain rate. μ_1 parameter is constant and is identified from tensile testing. On the other side, μ_2 is function of strain rate and its identification is based on compression testing. Each μ_2 parameter considered at constant strain rate is determined through the use of multi-objective optimization using global response surface method. Load measurements and strain gauge recording data are used to find a suitable parameter respectively for each quasi-static and high strain rate. The implementation of such constitutive model with special care for strain rate filtering is conducted in the explicit finite element code Radioss (Altair Hyperworks). In a concern of blunt trauma assessment, the authors decide to replicate on gel block the impact conditions of Bir reference cases, which are performed on postmortem human subjects (PMHS) [11]. These tests consist in the impact of round rigid projectile on the mid-sternum of PMHS. They represent important information in terms of autopsy results and quantitative data (load, sternum deflection). Model validity is evaluated by comparing experimental and numerical impact testing on gel block at different impact velocities. Figure 19.3 illustrates qualitative comparison of experimental impact (left) of 140 g projectile with 37 mm in diameter on gel block of size 25 × 25 × 25 cm, at 20 m/s and numerical modeling (right). It can be affirmed that numerical modeling and consequently constitutive material law is correctly described with an excellent representation of gel deformation.

To go further on the model effectiveness, experimental and numerical impact testing are carried out at several velocities: 12, 20 and 30 m/s. Gel wall displacement in function of time is chosen to correlate experimental and numerical testing (see Fig. 19.4). This comparison highlights satisfactory model abilities to describe blunt ballistic impacts by considering finite element modeling limits at very high deformation.

19.4 Conclusion

With an aim of assessing blunt ballistic trauma through the use of soft tissue simulant, mechanical characterization testing are performed on SEBS gel sample at various strain rates. Hyperelastic behavior with strain rate sensitivity is pointed out through specific tensile and compressive testing. Very high strain rates (until 1520 s^{-1}) are achieved using polymeric SHPB system. Numerical tools are adopted and a material constitutive law is implemented in the explicit code Radioss. Mooney-

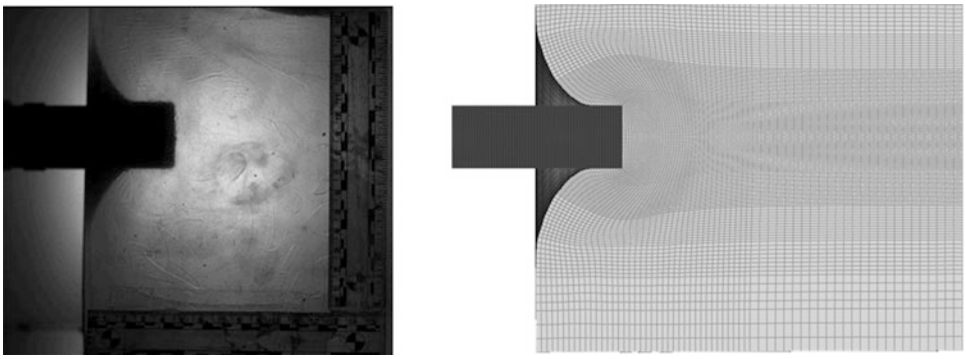

Fig. 19.3 Experimental (*left*) and numerical (*right*) impact testing on gel block at maximal deflection

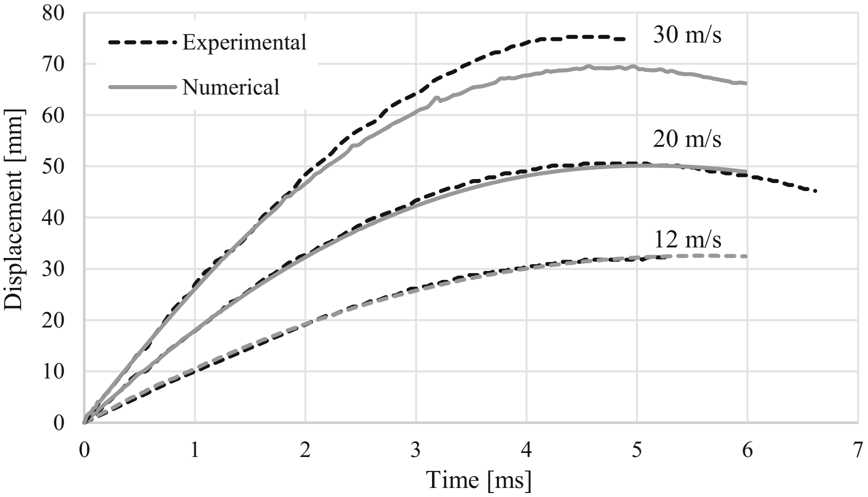

Fig. 19.4 Experimental and numerical gel wall displacement in function of time at impact velocities: 12, 20 and 30 m/s

Rivlin hyperelastic model is chosen and parameters are identified through the use of optimization by inverse method. Each mechanical testing and its numerical modeling are used to identify each parameter associated to a constant strain rate. Considering strain rate dependence in the constitutive model, experimental and numerical replications of Bir reference cases on gel block are performed at various impact velocities. Qualitative and quantitative data prove the model abilities to reproduce accurately blunt ballistic impacts. Therefore, extensive study on the evaluation of injury risk will be the focus of future investigations.

References

1. Mauzac, O., Paquier, C., Debord, E., Jacquet, J.F.: A substitute of gelatin for the measurement of dynamic back face deformation, presented at the Personal armour systems symposium, Canada (2010)
2. Mrozek, R.A., et al.: The relationship between mechanical properties and ballistic penetration depth in a viscoelastic gel. J. Mech. Behav. Biomed. Mater. **44**, 109–120 (2015)
3. Liu, L., Fan, Y., Li, W.: Viscoelastic shock wave in ballistic gelatin behind soft body armor. J. Mech. Behav. Biomed. Mater. **34**, 199–207 (2014)
4. Wen, Y., Xu, C., Wang, S., Batra, R.C.: Analysis of behind the armor ballistic trauma. J. Mech. Behav. Biomed. Mater. **45**, 11–21 (2015)
5. Casem, D.T., Dwivedi, A.K., Mrozek, R.A., Lenhart, J.L.: Compression response of a thermoplastic elastomer gel tissue surrogate over a range of strain-rates. Int. J. Solids Struct. **51**(11–12), 2037–2046 (2014)
6. Kolsky, H.: An investigation of the mechanical properties of materials at very high rates of loading. Proc. Phys. Soc. Sect. B. **62**(11), 676 (1949)
7. Salisbury, C.P., Cronin, D.S.: Mechanical properties of ballistic gelatin at high deformation rates. Exp. Mech. **49**(6), 829–840 (2009)
8. Van Sligtenhorst, C., Cronin, D.S., Wayne Brodland, G.: High strain rate compressive properties of bovine muscle tissue determined using a split Hopkinson bar apparatus. J. Biomech. **39**(10), 1852–1858 (2006)

9. Ogden, R.W.: Large deformation isotropic elasticity – on the correlation of theory and experiment for incompressible rubberlike solids. Proc. R. Soc. Lond. Math. Phys. Sci. **326**(1567), 565 (1972)
10. Rivlin, R.S.: Large elastic deformations of isotropic materials. IV. Further developments of the general theory. Philos. Trans. R. Soc. Math. Phys. Eng. Sci. **241**(835), 379–397 (1948)
11. Bir, C., Viano, D., King, A.: Development of biomechanical response corridors of the thorax to blunt ballistic impacts. J. Biomech. **37**(1), 73–79 (2004)